A 106.12:S-15
ISSN 0193-3779

Measurement and Prediction of Erosion and Sediment Yield

U.S. Department of Agriculture
Science and Education Administration
Agricultural Reviews and Manuals • ARM-S-15/April 1981

The research reported in this publication was done in cooperation with the Oklahoma Agricultural Experiment Station.

Trade names are used in this publication solely for the purpose of providing specific information. Mention of a trade name does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture or an endorsement by the Department over other products not mentioned.

This publication is available from the Science and Education Administration, P.O. Box 400, Chickasha, Okla. 73018.

Science and Education Administration, Agricultural Reviews and Manuals, Southern Series, No. 15, April 1981.

Published by Agricultural Research (Southern Region), Science and Education Administration, U.S. Department of Agriculture, P.O. Box 53326, New Orleans, La. 70153.

CONTENTS

ILLUSTRATIONS

TABLES

Measurement and Prediction of Erosion and Sediment Yield

By Paul B. Allen[1]

ABSTRACT

This paper reviews and illustrates equipment and procedures for measuring erosion from plots and sediment yield from watersheds; summarizes methods for predicting erosion and sediment yield; and cites many references that give more details about devices and methods surveyed here. Index terms: erosion, sedimentation, sediment samplers, sediment transport, sediment yield, sediment-yield computations, sediment-yield predictions.

INTRODUCTION

Recent emphasis on environmental pollution has greatly increased the need for monitoring and predicting soil erosion and sediment movement from all sizes of land areas. The U.S. Congress passed Public Law 92-500, "Federal Water Pollution Control Act Amendments of 1972," containing a section 208 that outlines methods for identifying and treating agriculturally related nonpoint sources of pollution. Both this act and the recognition that sediment transports chemical pollutants (such as plant nutrients, pesticides, and heavy metals) have led to increased efforts to control sediment.

Once, the U.S. Soil Conservation Service was the principal agency concerned with erosion and sediment yield in headwater watersheds. Today, however, many other county, city, State, and Federal agencies, and private firms and universities have become involved in research on erosion and sediment control, land-use planning, and land treatment; therefore many technical and professional workers are new to the field. To help inform them about measurement and prediction of erosion and sediment yield, this publication summarizes several methods, discusses their merits and limitations, and refers to many other publications that give more detailed information.

[1]Research hydraulic engineer, Southern Plains Watershed and Water Quality Laboratory, Science and Education Administration, U.S. Department of Agriculture, P.O. Box 400, Chickasha, Okla. 73018.

MEASUREMENT OF EROSION AND SEDIMENT YIELD

This section reviews equipment and procedures commonly used for sampling or measuring erosion and sediment yield for land areas ranging from small plots to large watersheds. Although one-of-a-kind equipment built for specific situations has been excluded, the equipment discussed will be adequate for most sediment monitoring. Some typical field data are also presented as guidelines to characteristics of sediment in transport.

Measurement Devices for Plots, Fields, and Small Watersheds

Collection tanks for total runoff

Collection tanks designed to hold the total runoff in 24 or 48 hours may be used to determine amounts of runoff and erosion from plots or very small fields. After each runoff event, service personnel must measure the water depth in the

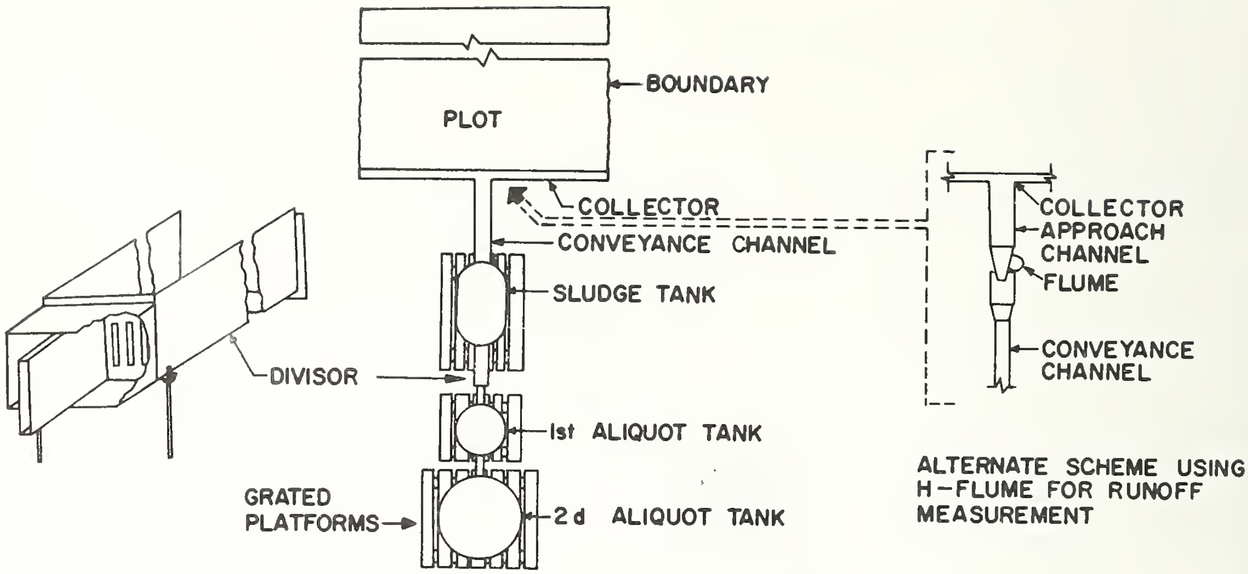

FIGURE 1.—Diagram of multislot divisor (after USDA Agriculture Handbook 224).

tanks, take representative samples for analyses of sediment concentration, and clean the tank for the next storm. Agriculture Handbook 224 (U.S. Science and Education Administration 1979) tells how to service the equipment and details calculation procedures for reducing field data to volume of runoff and quantity of erosion per unit of area. Although the device is simple, the tank is usually large, so servicing and installation costs may be higher than costs for other methods.

Multislot divisor

Because it retains only a fraction of the flow (one-third to one-thirteenth or less, depending on the design), the multislot divisor is often used to measure runoff and erosion from plots and fields. Figure 1 is a diagram of a typical installation. The first tank is a sludge tank; most installations have two aliquot tanks. Agriculture Handbook 224 gives detailed plans for various multislot divisors that will operate for flow rates up to 4 ft^3/s. Larger multislot divisors can be built from these plans.

After each runoff event, technicians determine water volumes in each tank and take samples so that laboratories can find sediment concentration. The data are then used to compute total runoff and sediment for the event. (Use Agriculture Handbook 224 for guidance.) An H-flume (fig. 1) could be used to provide a hydrograph of the event. Tank outlets must be above ground for easy cleanout, and the multislot divisor must be mounted above the tanks. Most installations require some excavation, and use of the divisor may be limited to land slopes greater than 2%-3%.

Coshocton sampler

Figure 2 shows the Coshocton sampler in a typical installation. A stage recorder mounted on the H-flume provides a complete hydrograph for each flow event. Water discharge from the H-flume falls on a slightly inclined water wheel, causing the wheel to rotate. An elevated sampling slot mounted on the wheel extracts a small sample during each revolution as the slot traverses the flow nappe. A small portion, usually 1% or less, of the flow is diverted through the slot and routed through the base of the wheel to a sample storage tank. The storage tank may be mounted below grade if adequate drainage is provided. Specifications and servicing instructions for several samplers that will measure peak flows up to 5½ ft^3/s are given in Agriculture Handbook 224.

Automatic pumping sampler

In the mid-1960's, battery-powered, automatic suspended-sediment samplers became available. Of the several samplers designed specifically for

FIGURE 2.—Coshocton sampler.

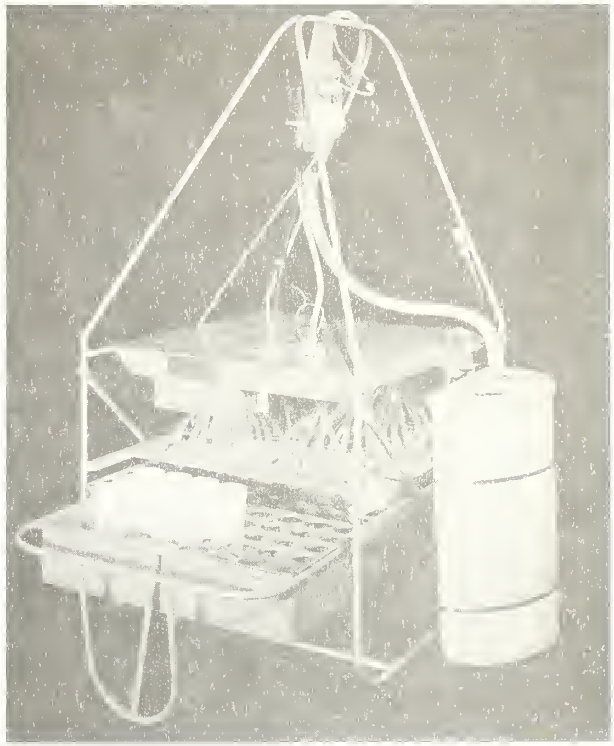

FIGURE 3.—U.S. PS-69 sediment sampler (photograph courtesy Federal Inter-Agency Sedimentation Project).

suspended sediment, only three are described here, because only they have been used enough over several years to be considered proven in the field. They are the U.S. PS-69 sampler (Federal Inter-Agency Sedimentation Project 1976), the Chickasha sampler (Allen et al. 1976), and a sampler manufactured by ISCO (3621 NW 36th Street, Lincoln, Nebr. 68524).

The U.S. PS-69 sampler (fig. 3) is available with either 72 pint bottles or 49 quart bottles. The quart-size samples are useful for analyses of trace elements, nutrients, and pesticides. The Chickasha sampler (fig. 4) holds 28 pint bottles but may be modified to hold 24 quart bottles. This sampler and the U.S. PS-69 sampler are available through the Federal Inter-Agency Sedimentation Project (St. Anthony Falls Hydraulic Laboratory, Hennepin Island and Third Avenue, SE, Minneapolis, Minn. 55414). The ISCO sampler, the smallest of the three, holds 28 500-ml beakers. All three samplers have provisions for varying the time between samplings.

Advantages of automatic pumping samplers over the collection tank for total runoff, multislot divisor, and Coshocton sampler are that they can be used for small or large drainage areas, sample volumes are small, less time is needed for servicing and cleanup, and samples obtained at specified time intervals provide data on sediment-discharge rates during each runoff event.

FIGURE 4.—Chickasha sediment sampler.

Among the disadvantages of pumping samplers are the generally higher cost of initial installation, the greater complexity of the equipment and its

maintenance, and the increased number of laboratory analyses and office calculations. The samples provide sediment concentrations only at specific time intervals, so a record of flow rate is needed because sediment discharge is determined by summing the products of concentration and waterflow rate for successive time intervals (see "Computing Sediment Discharge"). The device needed to measure this flow rate is usually a flume or weir.

Some problems associated with automatic pumping samplers are that generally only sand-size and smaller particles can be sampled; that, for streams with high sand loads, it is often difficult to find a sampler intake point that will provide samples representing the total sediment flow; and that flumes and weirs often cause sediment deposition immediately upstream and can therefore produce large errors in measurement of sediment yield unless the investigator keeps track of this deposition. Errors result not only from the sediment dropout but also from changes in the flume's or weir's discharge calibration caused by the deposition.

Very low altitude aerial photogrammetry

Most contour maps today are prepared with stereoplotters that allow operators to locate contour lines while viewing overlapping pairs of aerial photos (Piest et al. 1977). A rule of thumb is that the flight altitude divided by a constant, ranging from 1,000 to 1,500, determines the closest practical contour intervals that can be obtained. The U.S. Science and Education Administration (SEA) at Columbia, Mo., has successfully used this procedure to study erosion of cultivated fields (Piest et al. 1977) and gullies (R.F. Piest, personal communication). Photos taken with a camera suspended 60 feet above the ground were used to make maps with 0.1-foot contour intervals. This method is feasible only when erosion rates are very high.

Measurement Equipment and Procedures for Larger Watersheds

Ponds and reservoirs

For the purposes of this discussion, large watersheds are those having an area of more than about 1 or 2 mi^2. But ponds, which are used for measurements of yield from small watersheds, are discussed here with reservoirs because procedures are basically the same for both.

The U.S. Department of Agriculture and other government agencies have used measurements of sediment accumulation in ponds and reservoirs to determine watershed sediment yields. These ponds and reservoirs should have a high sediment-trap efficiency—the proportion of inflowing sediment that is trapped. Volumes of sediment deposits are usually determined by spudding or detailed volumetric surveys. Densities of sediment deposits may be determined with undisturbed samples or by nuclear methods. Agriculture Handbook 224 describes surveying and sampling equipment, procedures, and calculations.

More data on sediment yield in the United States is gained by this method than by any other. Results are published periodically, most recently in U.S. Department of Agriculture Miscellaneous Publication 1362 (Dendy and Champion 1978), which contains data on sediment accumulation for over 1,600 ponds and reservoirs.

Hand-operated equipment for sampling streamflow

Figure 5 shows four hand-operated suspended-sediment samplers commonly used to collect flow samples for determining sediment concentrations. The U.S. DH-48 is used for wading measurements, the U.S. DH-59 is suspended with a handline while the operator stands on a bridge, and the U.S. D-49 and U.S. P-61 are suspended from a reel on a cable car or suspended from a reel and crane on a bridge. The U.S. DH-48, U.S. DH-59, and U.S. D-49 are all depth-integrating samplers—the nozzle is always open and, because the sampler is lowered from the water surface to the streambed and raised back to the surface, the sampling rate at any point is proportional to the stream velocity. The depth-integration procedure produces a sample whose concentration is velocity-weighted throughout the flow depth (or discharge-weighted throughout the flow depth for an increment of flow width).

The U.S. P-61 sampler has an electric remote-controlled nozzle valve; this sampler can be used to collect either a depth-integrated sample, if the nozzle is left open continuously, or a point sample, if the sampler is lowered to any stream depth and the nozzle is opened for a time and then

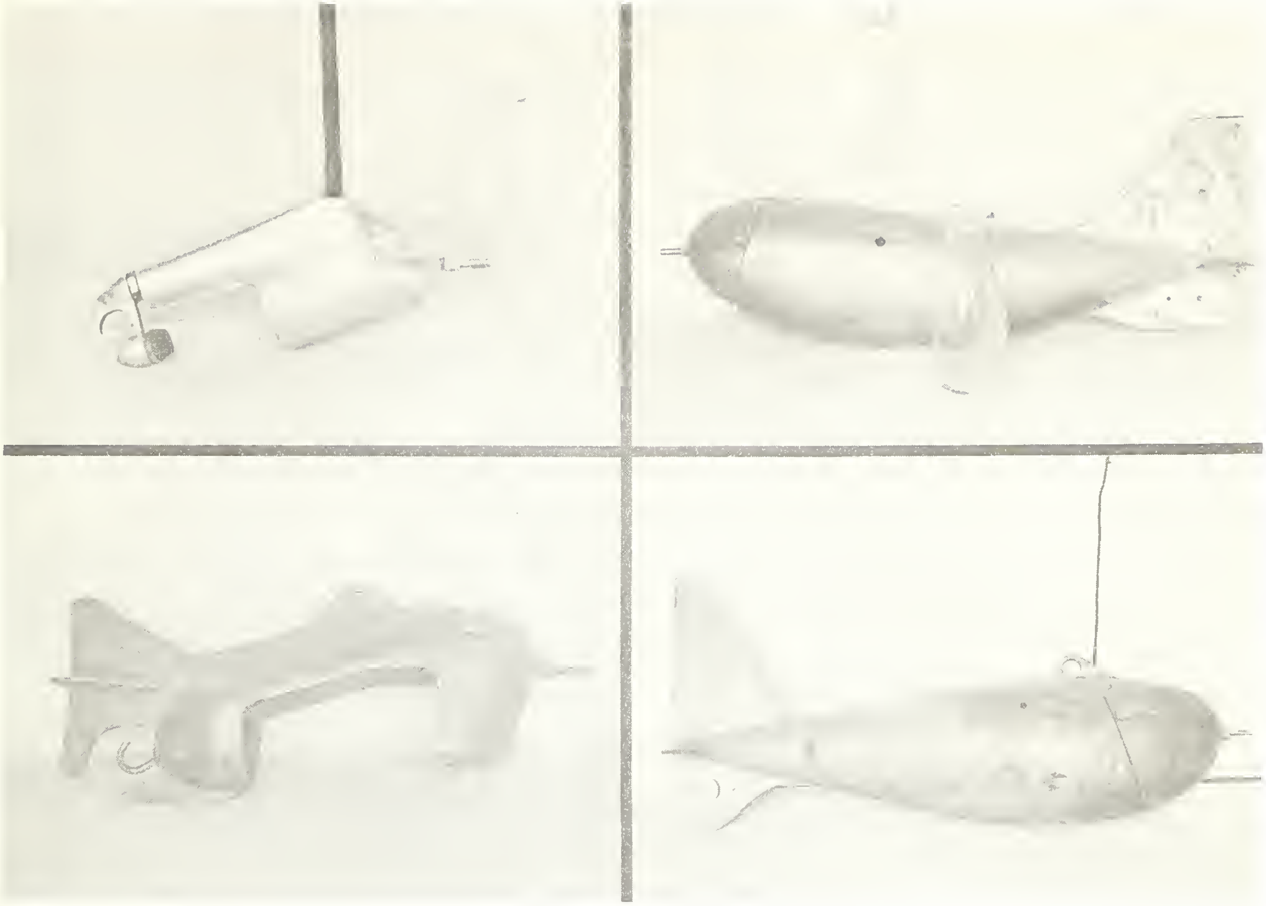

FIGURE 5.—Suspended-sediment samplers. Clockwise from upper left—U.S. DH-48, U.S. D-49, U.S. P-61, U.S. DH-59.

closed. For deep or swift flows, sampling by depth integration in one direction only is a common practice that decreases the sample volume and so extends the possible sampling depth. The U.S. P-63 sampler is like the U.S. P-61 sampler but weighs about twice as much. This sampler is used for flows deeper and swifter than those the U.S. P-61 can sample effectively.

Table 1 shows other specifications of these samplers. Although they all hold pint bottles, similar samplers are available that hold 1-quart containers. Also, each sampler is available with Teflon-coated metal parts that allow sampling for analyses of trace metals.

In sampling of a stream with depth-integrating samplers, the equal-transit-rate (ETR) method is usually used. For the sampler to get a discharge-weighted sample of the flow cross section, the sampled verticals must be equally spaced horizontally across the stream (fig. 6), and the sampler travel speed must be uniform. Agriculture Handbook 224 describes these measurements, telling how to choose the optimum number of verticals, how often sampling should be done, and what to record on a sample bottle—essential data such as gage height, time, temperature, and vertical number.

Information on cranes, reels, and auxiliary equipment needed for the hand-operated samplers may be obtained from U.S. Geological Survey Water-Supply Paper 888 (Corbett and others 1943) or from the nearest Surface Water Branch Office of the U.S. Geological Survey.

Automatic pumping samplers

The automatic samplers described earlier for plots, fields, and small watersheds are also widely used to sample runoff from larger watersheds. In some locations, where the sediment load is fine textured, automatic samplers may provide sediment concentration data that represent total

Table 1.—Specifications for suspended-sediment samplers[1]

Type and designation	Weight (pounds)	Length (inches)	Sample nozzle sizes (inch)	Sampling conditions and operation	Auxiliary equipment required
Depth-integrating:					
U.S. DH-48	4.5	13	3/16, 1/4	Wading depths and velocities.	Sampler is affixed to standard 1/2'' wading rod or small-diameter pipe.
U.S. D-49	62	24	1/8, 3/16, 1/4	Depths 15' to 18'. Low-to-moderate flow velocities. Sampler is usually operated from a bridge, cableway, or truck-mounted rig.	1/8'' steel cable, reel, and crane.
U.S. DH-59	22	15	1/8, 3/16, 1/4	Moderate depths and flow velocities, usually operated from bridge or cableway.	Handline or long suspended rod.
Point-integrating:					
U.S. P-61	105	28	3/16	Point-integrated samples to 150'. Also used to obtain 2-way depth-integrated samples to 18' in moderate velocities. Usually operated from bridge, cableway, or truck-mounted rig.	1/8'' steel, 2-conductor electrical suspension cable, reel and crane; 48-volt d.c. power source to operate sampler valve; additional power source to operate sampler and electric motor to operate reel.
U.S. P-63	200	34	3/16	Point-integrated samples to 180'. Depth-integrated samples in deep high-velocity streams. Usually operated from bridge, cableway, or truck-mounted rig.	Rugged 2-conductor steel suspension cable, reel, and crane; 48-volt d.c. power source to operate sampler and electric motor to operate reel.

[1]After USDA Agriculture Handbook 224. Sample volume for all samplers is 1 pint; U.S. P-61 and U.S. P-63 also have sample volumes of 1 quart.

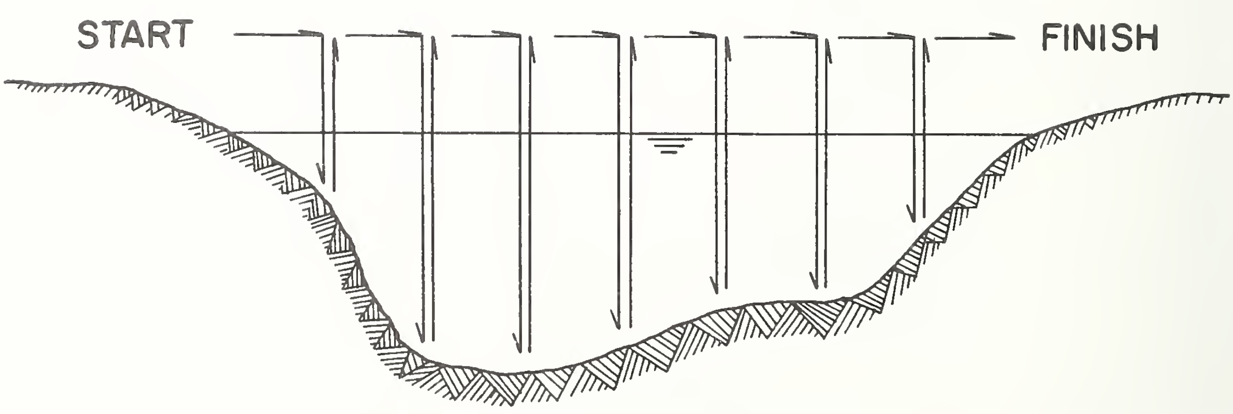

FIGURE 6.—Path of sampler for equal-transit-rate (ETR) measurement (from USDA Agriculture Handbook 224).

transport. In other locations, where the sediment load contains coarse material, ETR samples will be needed to establish a relation between the discharge-weighted mean concentration, as determined by the ETR sample, and the point concentration, as determined by the sample from the automatic sampler. At those locations where the relation varies, ETR samples will be needed periodically (but not as often as samples from the automatic sampler) for adjustments to the concentration record provided by automatic samples.

Locating automatic-sampler intakes that will provide representative samples is difficult at many installations, especially for wide, shallow streams and those streams with a load of coarse bed material. Most sampler intakes used today on large streams are attached to a structure fixed near midstream or near the channel bank. If nearly all the load is silt and clay, samples from such intakes usually represent the total flow. Samples from streams with large sand loads, however, are usually not representative. Intakes too near the bed or near a sandbar will produce concentrations that are too high. Intakes too far from the bed or in slow-moving water produce concentrations that are too low.

Pivoted-pipe intakes have been used that withdraw samples at a fixed fraction of total depth, such as mid-depth. These are actuated by a float, if they are pivoted near the bed. When the pipe is pivoted from a cable above the water, the frictional force exerted by the flow swings the pipe downstream. As the stream rises and the frictional force increases, the sampler's intake point will also rise.

Unsampled load (or unmeasured load)

Sediment discharge in a stream is computed by multiplying the water discharge by a discharge-weighted sediment concentration determined from suspended-sediment samples. The samplers shown in figure 5 will not sample the entire depth of flow in a natural stream because the nozzle is located above the sampler bottom. The unsampled depth near the streambed varies from 0.25 to 0.50 foot. Although the water discharge is known for the entire depth of flow, the concentration figure is usually wrong because of this unsampled depth. When coarse sediments are sampled, errors may be large because sediment concentrations increase towards the streambed, and the rate of increase is greater for coarse particles than for fine particles. When shallow flows are sampled, errors are larger because a greater percentage of the flow area is not sampled. Table 2 shows the general range of unsampled load for various combinations of streambed particle size, and suspended-sediment size and concentration.

Occasionally the total load can be sampled if circumstances are right—as, for example, in a highly turbulent flow resulting perhaps from a channel rock constriction. Total-load samples can also be obtained by sampling completely through the outfall from highway box culverts or other flow overfalls. Normally, however, predictive methods are used to calculate unsampled load. Two methods commonly used are the modified Einstein procedure (Colby and Hubbell 1961) and a method by Colby (1957).

Table 2.—Percentage of unsampled sediment load in various situations[1]

Streambed material	Texture of suspended material	Concentration of suspended load (p/m)	Unsampled load (percent of total)
Sand	Similar to streambed	<1,000	25-150
		1,000-7,500	10-35
		>7,500	2-8
Compacted clay, gravel, cobbles, and boulders.[2]	25% sand or less	<1,000	5-12
		1,000-7,500	5-12
		<7,500	5-15
Unconsolidated clay and silt	Clay and silt	Any	<2

[1]After Lane and Borland (1951).

[2]The bed material may contain any one of these very fine or coarse sediments.

The U.S. BM-54 bed-material sampler (U.S. Inter-Agency Committee on Water Resources 1963) shown in figure 7 is commonly used to collect samples from streambeds during flow events; these samples will give the gradation of the bed material. With this and other flow data, computations of unsampled load can be made with the modified Einstein procedure. These data on particle size can also be used with the several equations for bed-material load listed in "Predicting Erosion and Sediment Yield."

Although it is still undergoing performance tests, versions of the Helley-Smith sampler (Druffel et al. 1976) are being used to measure transport of coarse sediment on or near the streambed. This coarse sediment is essentially the bedload part of the unsampled load. The sampler is placed directly on the streambed for a timed interval, and a cloth-mesh container inside sifts particles according to mesh size.

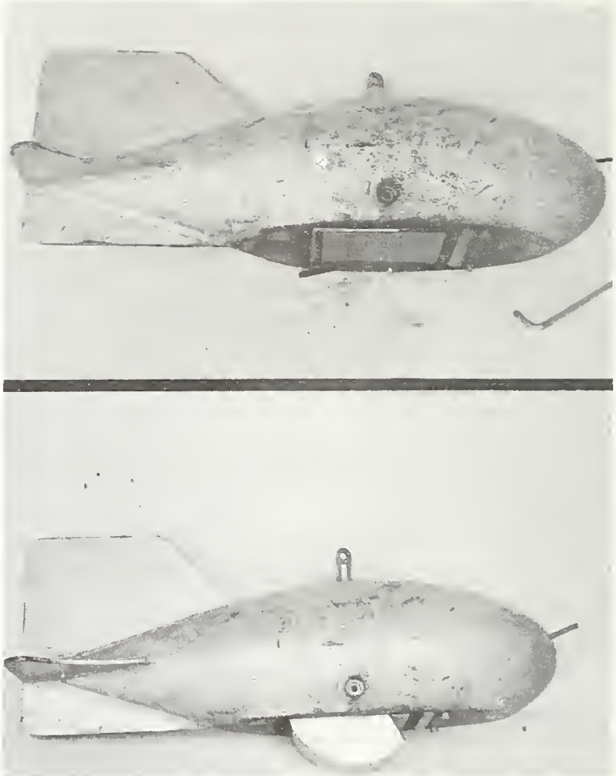

FIGURE 7.—U.S. BM-54 bed-material sampler. Top—bucket retracted; bottom—bucket partly closed.

Measuring channel and gully erosion

In some areas, about half the watershed sediment yield comes from gullies (Rhoades et al. 1975) and channels. Most channels and most gullies are irregular in shape, so accurate measurements of volumetric changes are difficult. Gully erosion occurs on any size watershed, but nearly all channel erosion is associated with larger watersheds, and measurement techniques for both are similar.

A channel measurement susally involves surveying (and documenting) a series of channel cross sections. A resurvey is made after enough time has elapsed for measurable erosion to take place (around 3 to 5 years on streams with visible erosion). Volumetric change between surveys can then be determined arithmetically or graphically.

The number of cross sections required will vary with the desired accuracy. On meandering streams with obvious bank erosion, cross sections must be placed in both straight reaches and bends, but with emphasis on the bends. SEA researchers at Chickasha, Okla., found that about half the erosion on a meandering stream was undetected when widely spaced cross sections were placed only on straight reaches.

Because gullies are normally more irregular than channels, researchers usually collect enough field data that a topographic map can be drawn with closely spaced contours (one-half foot is a practical interval. The field survey may be either closely spaced cross sections or a controlling point survey made with a plane table or transit, or it may be a combination of these. As with channels, an original survey and at least one resurvey are required for computing erosion. The computational procedures described in Agriculture Handbook 224 for determining reservoir deposition may be used in reducing field data on channels and gullies to erosion quantities.

In measuring gully erosion, using contour maps developed photogrammetrically has advantages over using those developed from conventional field surveys. For highly irregular terrain, maps produced photogrammetrically are generally more detailed; and where repetitive surveys are made, surveyors disturb fragile gully features little, if at all. SEA personnel at Columbia, Mo., are using this method to study gully erosion at Treynor, Iowa (R. F. Piest, personal communication). From photos taken 60 feet above the ground, maps can be made with contour intervals of 0.1 ± 0.05 foot, though the mapmakers use intervals of 0.25 or 0.5 foot for practical reasons; accuracy is still ± 0.05foot.

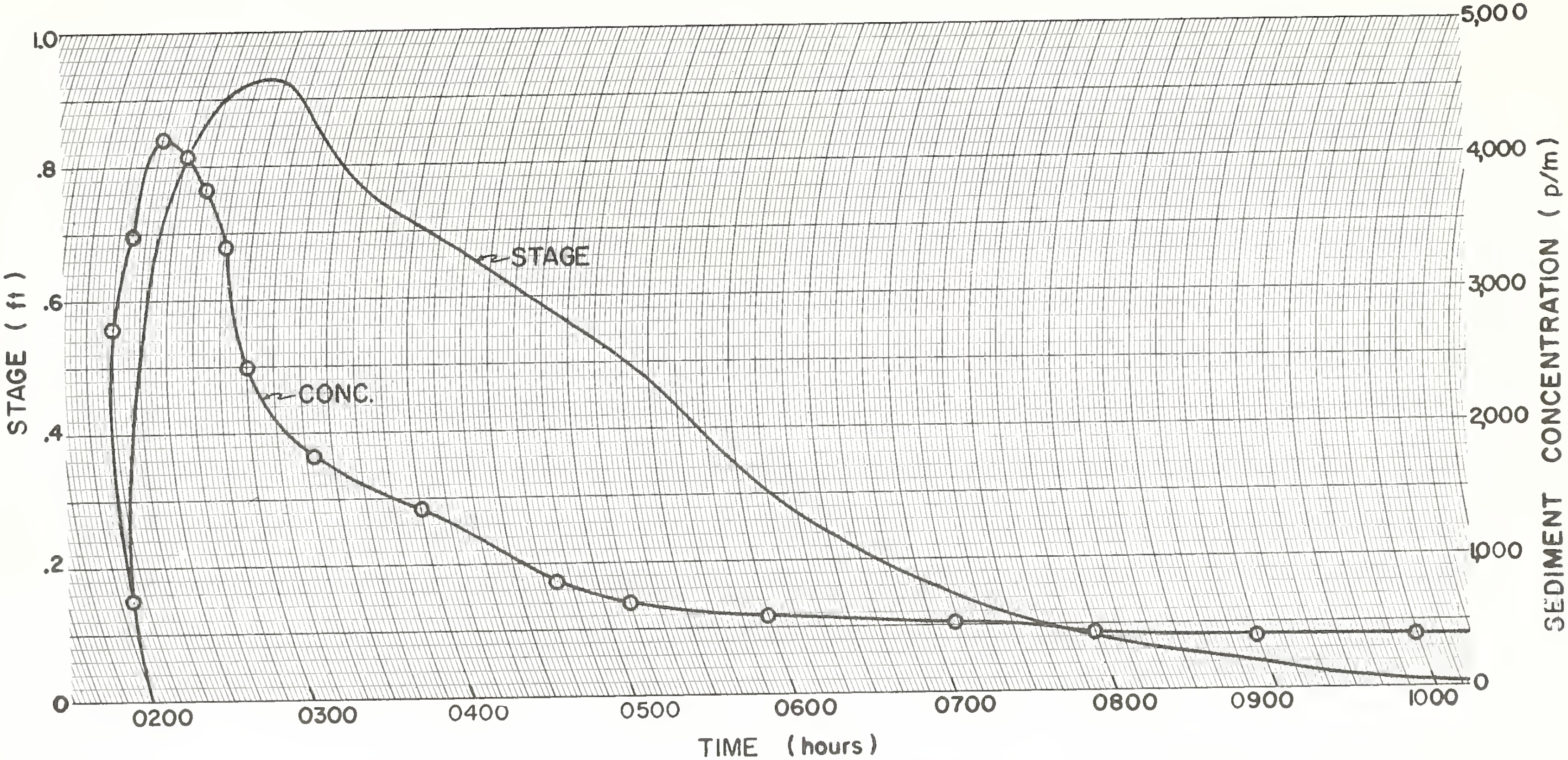

FIGURE 8.—Runoff hydrograph and sediment concentration curve for the October 9, 1968, flow event at SEA watershed C-3 near Chickasha, Okla. (after USDA Agriculture Handbook 224).

Flow measurement with periodic determinations of sediment concentration is also an accurate way to measure gully and channel erosion. Studies of channel erosion always require two gaging stations, at the beginning and end of the study reach with no intervening inflow. Gully erosion is usually measured with one station at the gully outlet. If significant erosion is in progress above the gully headcut, a second gaging station may be needed.

Computing Sediment Discharge

Collection tank for total runoff, multislot divisor, and Coshocton sampler

The concentration of sediment in the runoff and the rate or amount of runoff are required for calculations of sediment discharge for each flow event. For a collection tank, the volume of runoff in cubic feet is obtained from its depth-to-volume calibration. For a multislot divisor or a Coshocton sampler, dividing the volume of water (sample) by the sampling ratio gives the total runoff. To calculate sediment discharge, use the equation

$$G_s = 3.12CQ/(A \times 10^8),$$

where G_s = sediment discharge in tons per acre,
Q = storm water discharge in cubic feet,
C = storm-weighted concentration in p/m (parts per million) by weight,
and A = watershed area in acres.

For multislot divisors with more than one tank, the computation for water and sediment discharge must be made separately for each tank and the sediment results summed for the total sediment discharge.

The constant in the above equation assumes that the unit weight of the water-sediment mixture is 62.4 lb/ft^3. For concentrations above about 15,000 p/m, computed sediment discharges should be adjusted upwards with the density correction factors presented in Agriculture Handbook 224.

Location: Chickasha, Oklahoma — Water Constant: 0.016 ÷ Acres
Watershed: C-3 — Drainage Area: 44.3 Acres — Sediment Constant: 1.872 X 10^{-6}

Date (1)	Time (2)	Stage (ft) (3)	Concentration (p/m) (4)	Discharge (ft^3/s) (5)	Time Interval (minutes) (6)	Interval Concentration (p/m) (7)	Interval Water Discharge Rate (ft^3/s) (8)	Interval Runoff (inches) (9)	Interval Sediment Discharge (tons) (10)
10-9-68	0200	.00	0	.000					
	0205	.15	750	.070	5	375	.035	0.0001	.000
	0210	.26	2800	.321	5	1175	.1955	.0004	.003
	0215	.41	3500	1.119	5	3150	.720	.0013	.021
	0220	.54	4200	2.369	5	3850	1.744	.0033	.063
	0223	.65	4175	3.917	3	4187.5	3.143	.0035	.074
	0226	.73	4150	5.362	3	4162.5	4.6395	.0052	.108
	0230	.81	4075	7.100	4	4112.5	6.231	.0093	.192
	0234	.86	4000	8.346	4	4037.5	7.723	.0115	.233
	0240	.90	3825	9.434	6	3912.5	8.890	.0199	.391
	0246	.92	3650	10.010	6	3737.5	9.722	.0218	.408
	0250	.93	3400	10.300	4	3525	10.155	.0152	.268
	0300	.93	2500	10.300	10	2950	10.300	.0384	.569
	0309	.90	2125	9.434	9	2312.5	9.867	.0331	.384
	0314	.87	2000	8.610	5	2075	9.022	.0168	.175
	0323	.83	1825	7.584	9	1912.5	8.097	.0272	.261
	0334	.79	1700	6.637	11	1762.5	7.1105	.0292	.258
	0400	.71	1425	4.974	26	1562.5	5.8055	.0563	.441
	0420	.66	1200	4.082	20	1312.5	4.528	.0338	.223
	0445	.60	875	3.153	25	1037.5	3.6175	.0037	.176
	0510	.54	700	2.369	25	787.5	2.761	.0257	.102
	0529	.48	650	1.720	19	675	2.0445	.0145	.049
	0544	.42	625	1.195	15	637.5	1.4575	.0082	.026
	0600	.35	600	.726	16	612.5	.9605	.0057	.018
	0618	.29	575	.433	18	587.5	.5795	.0039	.011
	0632	.24	550	.257	14	562.5	.345	.0018	.005
	0650	.19	550	.135	18	550	.196	.0013	.004
	0709	.15	525	.070	19	537.5	.1025	.0007	.002
	0728	.12	500	.037	19	512.5	.0535	.0004	.001
	0800	.08	450	.012	32	475	.0245	.0003	.001
	0830	.06	425	.005	30	437.5	.0085	.0001	.000
	0900	.04	400	.002	30	412.5	.0035	.0000	.000
	0928	.03	400	.001	28	400	.0015	.0000	.000
	1000	.02	400	.000	32	400	.0005	.0000	.000
						TOTALS		.4226	4.467

FIGURE 9.—Form for sediment-discharge computations (after USDA Agriculture Handbook 224).

Continuous-concentration curve

For plots, fields, or watersheds where suspended-sediment samples are taken periodically during flow events, the continuous-concentration curve may be used to compute sediment discharge. Sediment concentrations are plotted on the water-stage chart, and a continuous-concentration line is drawn (fig. 8). Concentrations and stages are picked at selected times (usually curve breakpoints) throughout the runoff event and recorded (fig. 9; columns 2-4). Each stage is converted to a discharge rate (column 5) through a stage-to-discharge relation developed for the gaging station. Time intervals and mean concentrations and discharges are computed and recorded (columns 6-8). Runoff volume in inches for each interval (column 9) is the product of time interval, mean discharge, and the water constant, 0.016÷acres. "Interval sediment discharge" in tons (column 10) is the product of time interval, mean concentration, mean discharge, and the sediment constant, 1.872×10^{-6}. Summing runoff volumes gives the total runoff for the flow event, and summing "internal sediment discharge" gives total sediment discharge.

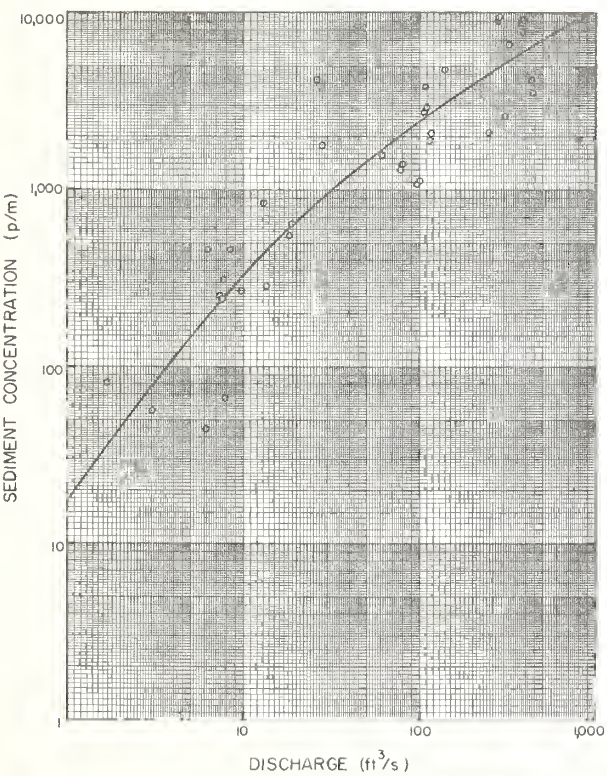

FIGURE 10.—Sediment-rating curve for Winter Creek near Alex, Okla.

Sediment-rating curve

Since it was first introduced in 1940, the flow-duration, sediment-rating-curve procedure has been widely used. This method is described in treatises by Miller (1951) and Colby (1956). It requires far fewer samples than the continuous-concentration-curve procedure and therefore costs less but is also less accurate. Gaged runoff data are required and must cover the desired computational period, which can vary from one runoff event to runoff for several years. Data on suspended sediment need not be from the same period, but results are more accurate if they are, especially for a single runoff event.

The method uses the general relation of sediment-transport rate and waterflow rate that exists for most streams. Figure 10 shows a typical sediment-rating curve (from data for 1 year) plotted on log-log paper. For computations of sediment discharge, the runoff data must be divided into flow-rate ranges, and the time of flow in each range must be determined and recorded (fig. 11). The concentration at each flow-rate midpoint must be picked from the sediment-rating curve and recorded (fig. 11). The tons of sediment transport for each flow-rate range is the product of the midpoint flow rate, the number of hours, the concentration, and the constant 1.123×10^{-4} For watersheds larger than about 500 mi², the time column may be in days, and data on mean daily flow may be used. For smaller watersheds, however, it is best to use hourly time increments because large errors occur in computing sediment transport for the higher flows. On a small stream, for example, a runoff event with a peak flow of 1,000 ft³/s may have a mean daily flow rate of only 60 or 70 ft³/s.

Some Characteristics of Sediment Discharge

Figures 12-15 show some general trends and characteristics of sediment concentrations during runoff events. Figure 12 is the concentration graph and hydrograph for a large intense rainstorm on a 35-mi² watershed. Notice that the sediment concentration rose sharply during the early part of

Water Discharge Range (ft^3/s)	Water Discharge Midpoint (ft^3/s)	Time (hours)	Sediment Conc. (p/m)	Sediment Transport (tons)
0 - 5	2.5	7844.4	60	132.1
5 - 10	7.5	432.4	210	76.5
10 - 15	12.5	156.7	330	72.6
15 - 20	17.5	43.7	435	37.4
20 - 25	22.5	43.9	540	59.9
25 - 30	27.5	36.5	645	72.7
30 - 35	32.5	10.8	750	29.6
35 - 40	37.5	30.1	830	105.2
40 - 45	42.5	5.8	930	25.7
45 - 50	47.5	26.4	1,020	143.6
50 - 55	52.5	5.3	1,100	34.4
55 - 60	57.5	6.6	1,160	49.4
60 - 65	62.5	.3	1,280	2.7
65 - 70	67.5	30.4	1,380	318.0
70 - 75	72.5	5.2	1,440	61.0
75 - 80	77.5	3.5	1,550	47.2
80 - 85	82.5	26.7	1,610	396.3
85 - 90	87.5	1.2	1,710	20.1
90 - 95	92.5	4.9	1,800	91.6
95 - 100	97.5	1.3	1,900	27.0
100 - 105	102.5	5.0	2,000	115.1
105 - 110	107.5	.7	2,100	17.7
110 - 115	112.5	3.0	2,150	81.5
115 - 120	117.5	1.3	2,250	38.6
120 - 125	122.5	2.5	2,300	79.1
130 - 135	132.5	3.5	2,480	129.2
135 - 140	137.5	.6	2,550	23.6
145 - 150	147.5	3.5	2,700	156.5
155 - 160	157.5	3.0	2,800	148.6
165 - 170	167.5	4.6	3,000	259.6
180 - 185	182.5	.7	3,180	45.6
185 - 190	187.5	1.9	3,250	130.0
200 - 205	202.5	.2	3,350	15.2
205 - 210	207.5	.6	3,500	48.9
210 - 215	212.5	.6	3,580	51.3
215 - 220	217.5	.1	3,650	8.9
220 - 225	222.5	1.7	3,700	157.2
225 - 230	227.5	.2	3,750	19.2
235 - 240	237.5	.8	3,900	83.2
275 - 280	277.5	1.5	4,250	198.7
280 - 285	282.5	.6	4,300	81.9
320 - 325	322.5	.7	4,700	119.2
355 - 360	357.5	.3	5,050	60.8
375 - 380	377.5	.2	5,250	44.5
380 - 385	382.5	2.0	5,300	455.3
385 - 390	387.5	.3	5,350	69.8
390 - 395	392.5	.2	5,380	47.4
400 - 405	402.5	.2	5,400	48.8
415 - 420	417.5	.2	5,450	51.1
445 - 450	447.5	.5	5,500	138.2
450 - 455	452.5	.5	5,550	141.0
470 - 475	472.5	.2	6,000	63.7
480 - 485	482.5	.1	6,050	32.8
525 - 530	527.5	.3	6,350	112.8
530 - 535	532.5	.8	6,380	305.2
580 - 585	582.5	.2	6,650	87.0
585 - 590	587.5	.2	6,700	88.4
590 - 595	592.5	.4	6,750	179.7
			Total	5,740.4

FIGURE 11.—Computational form for the method using the sediment-rating curve of figure 10 and flow data for 1977 from Winter Creek near Alex, Okla.

the runoff and peaked long before the runoff peaked, probably because of soil detachment by rainfall during the initial flow to the channel system. At some gaging sites, concentration graphs may have several small concentration peaks early in the hydrograph caused by inflow from nearby tributaries, road ditches, etc. These small peaks are short lived, however, and are rarely defined in most sampling programs. The resulting transport error is small because the initial flow rate is low.

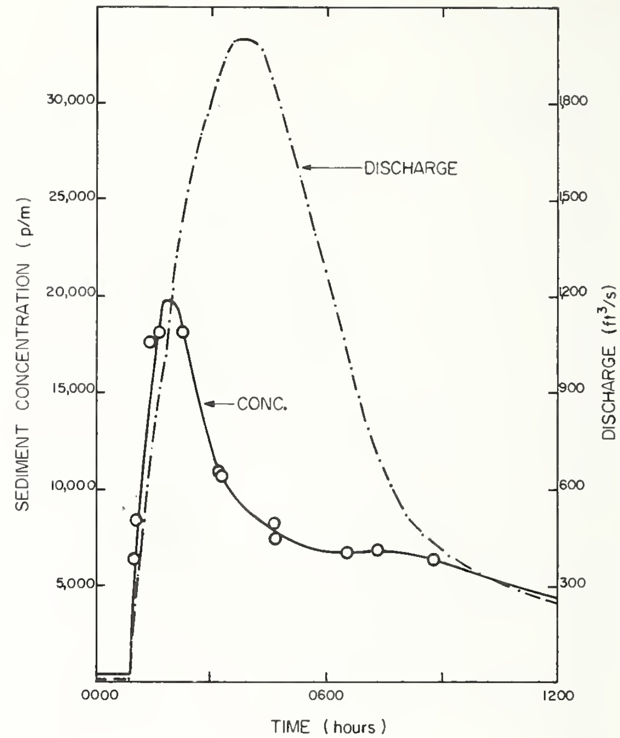

FIGURE 12.—Hydrograph and sediment graph for the June 8, 1971, flow event at West Bitter Creek near Chickasha, Okla.

After the peaks, most concentration graphs are fairly smooth because of the blending action of secondary currents in the flow.

In contrast to the large, high-intensity rainfall event shown in figure 12, figure 13 shows runoff from a small, low-intensity rainstorm for the same watershed. The concentration graph is low and flat, and the peak sediment concentration more nearly coincides with the peak flow. Where most runoff occurs in the upper part of a large watershed, the concentration peak may lag behind the runoff peak. This effect occurs because floodwaves in channels move downstream faster than the particles of water and sediment.

Figure 14 shows the data used in figure 12 where transport rate is plotted against flow rate. On log-log paper the rising leg and the falling leg approach a straight line; so transport is a power function of flow rate. Most flow events exhibit the loop effect (fig. 14) that reflects the usually higher concentrations on the rising side of the hydrograph. If more rain and runoff occur during a runoff event, more loops appear on diagrams of the relation of transport rate and flow rate. These diagrams are useful for supplying missing

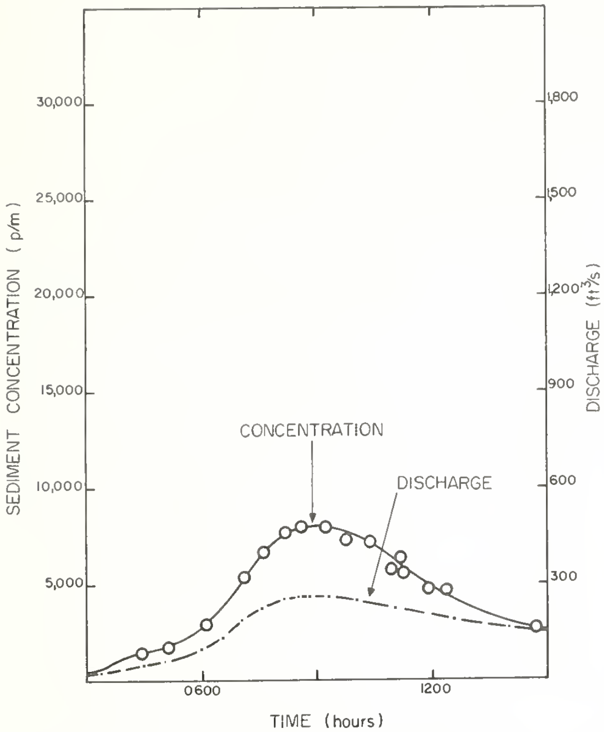

FIGURE 13.—Hydrograph and sediment graph for the October 11, 1973, flow event at West Bitter Creek near Chickasha, Okla.

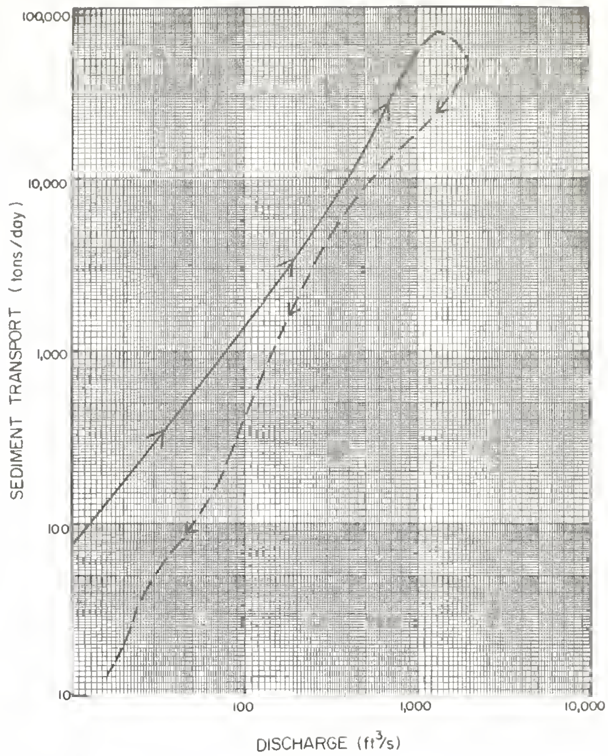

FIGURE 14.—Typical loop in the relation of sediment transport and discharge for the June 8, 1971, flow event at West Bitter Creek near Chickasha, Okla.

concentration data for those runoff events when field personnel or pumping samplers do not get enough samples.

Many samples have been collected and analyzed for total sediment concentration. Although some of these samples were analyzed for the percent and gradation of sand, few were analyzed for silt and clay content. Figure 15 shows one runoff event where data on silt and clay were available. Most variation occurred in the silt and sand part of the load. The concentration of clay-size particles remained fairly constant throughout the storm. Determinations of particle size for the data of figure 15 were made with the flow samples in their natural state without the addition of a dispersing agent. Had a dispersant been added, many silt-size aggregates would have separated into clay-size material.

PREDICTING EROSION AND SEDIMENT YIELD

Data for predicted erosion and sediment yield are always less accurate than measurements. Few measurements are available, however, especially for small watersheds. Measurements also cost more and require lengthy data-collection periods to establish long-term yields. So methods for predicting erosion and sediment yield are necessary for land-use planning, basin planning, assessing land treatment measures, and designing reservoirs. Several prediction methods are reviewed below.

Gross Erosion From Field-Size Areas

The universal soil-loss equation (USLE) is the most widely known and used equation for estimating gross erosion from upland areas (excluding gullies, channels, and landslides). More than 40 years of erosion research by the U.S. Department of Agriculture in cooperation with State agricultural experiment stations has identified the major factors and determined factor values for computing rates of soil loss. Although the equation's applicability is limited in some areas by the lack of data that define factor values,

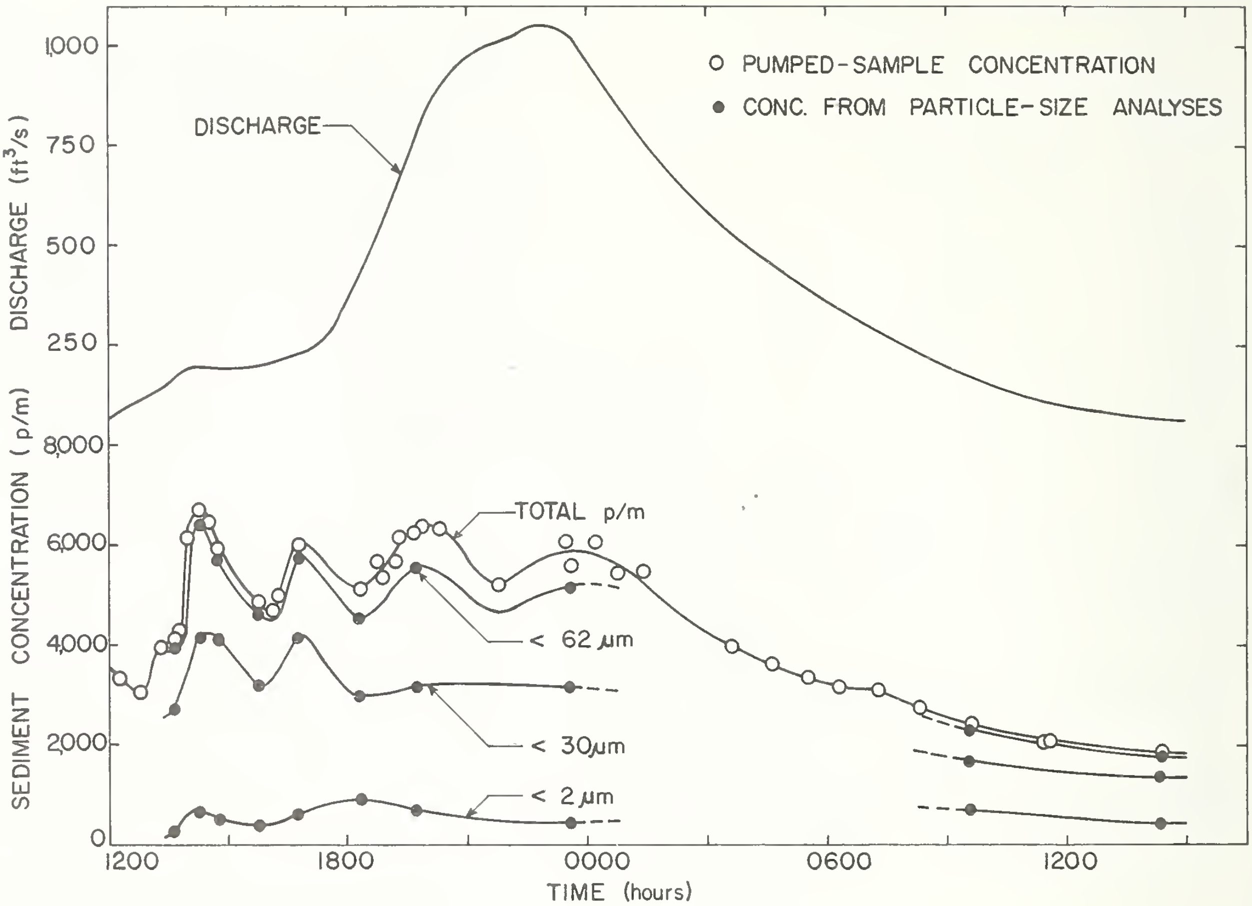

FIGURE 15.—Variation of discharge and the concentration of sand, silt, and clay during the September 22-23, 1970, flow event at West Bitter Creek near Chickasha, Okla.

enough information is available that the equation can provide useful estimates of erosion on most cropland, pasture, and rangeland in the United States. In the USLE,

$$A = RKLSCP,$$

where A = the estimated annual soil loss in tons per acre.

R = the rainfall-erosivity factor determined from rainfall amounts and intensities; R values may be obtained by interpolating between iso-value lines on published maps.

K = the soil-erodibility factor, which can be obtained from the SCS K-value listings for most soil series in the United States, or from a nomograph if the texture, organic matter, structure, and permeability of a soil is known or can be estimated.

L = the slope-length factor, which can be approximated by (slope length/72.6)^m, where m=0.5 for slopes steeper than 4%, 0.4 for slopes of 4%, 0.3 for slopes of 1% to 3%, and 0.2 for slopes less than 1%.

S = the slope-steepness factor; it is defined by the relation $S = (430 \sin^2 \Theta + 30 \sin \Theta + 0.43)/6.574$, where Θ = the angle of slope. (In practice, L and S are combined into a single factor and determined from published graphs.)

C = the cover and management factor; it is the ratio of the soil loss with specified cover and agronomic practices to that from the fallow condition where K was determined. C-values at different crop stages may be obtained from published tables. The C-value for the entire year is obtained by weighting the C-values for crop-stage periods with the R associated

with each period.

P=a supporting-practices factor; it is like C, but P accounts for additional practices such as contouring, terracing, diversion, and contour stripcropping. Values of P are available from published tables.

Stewart et al. (1975), Wischmeier (1976a), and Wischmeier and Smith (1978) are good general articles about the USLE. Wischmeier (1976b), in reviewing the use and misuse of the equation, lists seven applications for which the equation was specifically designed and field-tested. He cautions that soil loss is not the same as sediment yield where deposition has occurred at the toes of slopes, along field boundaries, and in terrace channels. He also explains that large errors may occur when storm R-values are used to predict soil losses caused by storms. The USLE best predicts average annual losses or average losses for specific crop-stage periods.

When the USLE was checked against 2,300 plot-years of soil-loss data from 189 field plots where the measured mean annual soil loss was 11.3 tons/acre, the average prediction error was 1.4 tons/acre, and 84% of the predictions were within 2 tons/acre of the measured losses. Only 5% of the predictions differed from measured losses by more than 4.5 tons/acre.

Predicting Sediment Yield From Watersheds

The concern with environmental pollution has intensified the development of methods to estimate sediment yield from watersheds. The methods fall in four general categories.

The USLE and the sediment-delivery ratio

The delivery ratio is defined as the ratio of sediment delivered at a point in the stream system to the gross erosion from all sources in the watershed above that point. Although USLE estimates account for deposition in manmade devices such as terraces near the sediment source, the delivery ratio must adjust USLE estimates downward to compensate for deposition along field boundaries, at the toes of slopes, and along channels and alluvial valleys. It must also account for sediment additions along the transport paths such as gullies, streambanks, and streambeds. Guides for estimating delivery ratios are presented in the U.S. Soil Conservation Service Technical Guide 12 (1976).

Reports on prediction accuracy when delivery ratios are used are few and contradictory. Findings of Maner and Barnes (1953) and Dendy and Bolton (1976) support the delivery-ratio principle. But studies by Spraberry et al. (1960) and hydrologic data collected from the Great Plains (U.S. Science and Education Administration, unpublished) show no relation of sediment yield to drainage area. Logic suggests that to expect a simple relation to account for such diversity in additions and depositions of watershed sediment is overly optimistic.

The modified USLE (MUSLE)

Sediment yield in most watersheds is limited by sediment deposition. Deposition results when sediment supply exceeds runoff transporting capacity. Sediment yield is therefore strongly related to flow characteristics and less directly to rainfall characteristics. Williams (1975) found that replacing the R-factor in the USLE with a term for runoff intensity could eliminate the need for a delivery ratio for many situations. This modified USLE (MUSLE) is

$$G=\alpha(Qq_p)^{\beta}KLSCP/Ac,$$

where G=the storm-event sediment yield in tons/acre,

Q=the storm-event runoff volume in acre-feet,

q_p=the storm-event peak flow in cubic feet per second,

Ac=the drainage area in acres,

α, β=coefficients,

and other terms are as defined above.

For watersheds in Texas and Nebraska, the coefficient α was 95, and β was 0.56. These coefficients are known to vary and must be determined in other locations. Annual sediment yields are obtained by summing yields from storm events.

Empirical procedures

Rather than extrapolate the USLE to large areas, researchers have derived empirical sediment-yield equations directly from observed watershed sediment data. Like the USLE, these equations

generally include factors known to have a major effect on sediment yield. Although many equations have been proposed, I will describe only two typical examples.

Flaxman (1972), using standard multiple-regression techniques and 39 sets of data collected across 9 Western States, developed an equation for watershed sediment yield, Q_S, in acre-feet per square mile. In this equation,

$$Q_s = 1.633\times10^6(P/T+100)^{-2.191}(S+100)^{0.0603}(Co+100)^{-0.0164}(AG+100)^{-0.0425}-100,$$

where P = the average annual precipitation in inches,
T = the average annual temperature in degrees Fahrenheit,
S = the average slope of the watershed in percent,
Co = the percentage of particles coarser than 1.0 mm in the surface 2 inches of soil,
and AG = an indication of aggradation or dispersion of the clay particles. Values are the percentage of clay in the surface 2 inches of soil. The sign of each value is related to the pH of the soil, positive for pH>7.0 and negative for pH$\leq$7.0.

Estimates of sediment yield by the Flaxman equation are sensitive to changes in the P/T ratio but relatively insensitive to changes in the other variables.

Another example of the empirical procedure is the group of four sediment-yield equations by Hindall (1976) for the four geographic provinces in Wisconsin. With the proper equation, mean annual sediment yield can be computed at any point on almost any stream in the State.

Each of his equations uses one to nine of the following independent variables that can be measured or obtained from published data: drainage area; average daily discharge; the discharge for the 2-year recurrence interval; the discharge for the 25-year recurrence interval; main channel slope; percentage of drainage area in lakes, ponds, or wetlands; length of the main channel; percentage of drainage area in forests; an index of soil infiltration capacity; 24-hour maximum rainfall that has a recurrence interval of 2 years; the discharge for the 10-year recurrence interval, divided by the drainage area; a vegetation factor determined by dividing the mean annual precipitation by the mean annual temperature; the mean February 28 frost depth; and an index of streamflow duration determined by dividing the discharge occurring 10% of the time by the discharge occurring 90% of the time. Hindall (1976) gives the specific equations and the regression coefficients.

Other examples of empirical equations include those by Anderson (1949), Baird (1964), Striffler (1964), Williams et al. (1971), Betson (1976), and Dendy and Bolton (1976). Generally, empirical equations give fairly reliable predictions for areas that have vegetation, physiography, and climate in common with the areas for which the equations were developed. If an empirical equation is used to predict sediment yield from a dissimilar area, large errors may result.

Physically based, distributed-parameter models

Most watershed simulation procedures use averaged or lumped data for precipitation, antecedent moisture, cover, slopes, soils, etc. Recently, watershed simulation models have been developed that use distributed data so that hydrologic response can be simulated point by point. Generally, these models describe with algorithms the erosion processes of detachment by rainfall, detachment by runoff, and transport by runoff. Such models, when sufficiently perfected, should be better than other procedures for accurately predicting sediment yields, determining the hydrologic effects of watershed treatments, and showing where erosion and deposition are occurring in the watershed.

Table 3 lists some of these models. Those listed are driven by runoff models, also physically based, that generally simulate rainfall interception, surface detention, infiltration, and excess rainfall routing. ACTMO (agricultural chemical transport model) (Frere et al. 1975) also predicts runoff of plant nutrients.

The models use various procedures to subdivide watersheds. In ACTMO, a watershed is divided into several zones representing the elevation sequence of uplands, hillsides, and bottomlands. The zones are transformed to rectangular planes of equivalent area; each plane is divided into flow tubes representing the areas that drain to streams across no lower zone, one lower zone, two lower zones, etc.

In the Colorado State University model (Simons et al. 1975), a grid is laid over a topographic map of the watershed. The grid helps researchers select subareas and assign flow direction for each. Segments for channel length and road length are also selected. The areas, channel segments, and

Table 3.—Some characteristics of three physically based, distributed-parameter models

Model name	Agency or institution	Runoff model used	Watershed divisions	Calibration needed ?	Prediction time span
ACTMO	USDA	USDAHL	A few slope zones transformed to equivalent-area and equivalent-length rectangular planes. Each plane is divided into flow tubes representing areas that drain to streams across no lower zone, 1 lower zone, 2 lower zones, etc.	No	Continuous.
Colorado State University.	Colorado State University.	New	Irregular areas, channel segments, and road segments arranged in numerical sequence for computing of runoff.	Yes	Storm.
ANSWERS	Purdue University.	Huggins and Monke.	Gridded cells, each with flow direction. Some cells serve 2 ways for channels.	No	Storm.

road segments are then arranged in a numerical sequence that follows a logical pattern of gravity flow. This sequence is used iteratively in the computing of excess rainfall and runoff and of sediment routing.

In ANSWERS (areal nonpoint source watershed environmental response simulation) (Beasley et al. 1977), a watershed is gridded into square cells, and each cell is assigned a downslope (or flow) direction. Runoff is simultaneously simulated for all cells from the rainfall in each time increment. Some cells serve both for runoff simulation and for a channel increment. The output from some cells becomes the input for other cells; the result is a hydrograph for each cell and a composite hydrograph for the entire watershed.

ANSWERS and the Colorado State University model determine sediment yield with algorithms that define detachment by rainfall, detachment by runoff, and transport by runoff. ACTMO defines sediment yield with a modification of the USLE by Foster et al. (1977), where the term for rainfall energy has been replaced with a term that reflects the contribution of both rainfall and runoff. These three models use the concept of limited transport and limited supply. If the sediment inflow and sediment detached by rainfall exceed transport capacity for any areal increment, deposition occurs and the sediment yield is the transport capacity. But if the sediment supply is less than the transport capacity, the sediment yield consists of the supply plus any sediment detached by the flow.

Some of the models require calibration of parameters with observed hydrologic data. This procedure is generally considered less desirable than fully deterministic models where all parameter values can be determined by measuring watershed component properties or with published guides. ACTMO and ANSWERS are mainly deterministic models. The Colorado State University model, however, requires calibration for two sediment parameters.

Two of the models predict the texture of the sediment yield. The Colorado State University model predicts wash load (often assumed to be silt and clay) and any selected fractions of the bed-material load. ACTMO predicts two fractions—silt-clay and sand. ANSWERS predicts only the total sediment yield.

The accuracy of these models has not been fully determined. At present they may be no more accurate than other, simpler procedures. But because of the current emphasis on environmental pollution, these and other models are being intensively refined. Although limited by uncertain accuracy, greater difficulty of use, and large computer requirement, the models may still be useful for planning purposes because they show yield under various land uses and delineate areas of excessive erosion and deposition.

Equations for Predicting Transport of Bed Material

Many equations have been developed to predict sediment transport in streams. (Some contain graphic elements, but all are called equations in this discussion.) Such equations have been widely used in planning river regulation projects and channel modifications. Under altered flow regimes, the equations assist with estimates of channel scour or fill so that eventual streambed elevations

Table 4.—Equations for predicting transport of bed material

Type	Equation	Year introduced	Reference
Discharge	Schoklitsch	1934	Shulits and Hill (1958).
	Meyer-Peter	1934	
	Casey	1935	
	Haywood	1940	
	Schoklitsch	1943	
Tractive force.	Straub-DuBoys	1935	Shulits and Hill (1958).
	Waterways Exp. Stn.	1935	
	Shields	1936	
	Elzerman and Frijlink	1951	
Dimensionless parameter.	Laursen	1957	Shulits and Hill (1958).
	Engelund and Hansen	1967	Engelund and Hansen (1967).
	Ackers and White	1973	Ackers and White (1973).
Velocity	Colby	1964	Colby (1964).
Einstein	Einstein	1950	Einstein (1950).
	Toffaleti	1968	Toffaleti (1968).
Stream power	Bagnold	1966	Bagnold (1966).
	Yang	1972	Yang (1972).

and slopes can be approximated. The equations are also useful in the designing of stable channels that must transport sediment. Some equations are being used in the new, physically based models of watershed sediment yield to compute sediment transport in channels and overland flow. When a watershed has both upland soils that are predominantly sandy and a main channel with a sandy bed, then watershed sediment yield may be approximated with such equations.

Table 4 lists many of these equations, their principal type, and their dates of introduction. Although space does not permit inclusion of the actual equations, a reference is given for each. The compilation by Shulits and Hill (1968) has been used as a reference wherever possible. Because of the experimental data used, these equations probably best predict bed-material transport—the movement of the size of particle predominating in the shifting portion of the streambed. Bed-material transport (or load) consists of bed-load—those particles moving next to and supported by the streambed—and suspended bed-material load—particles suspended by the flow turbulence and found anywhere in the flow cross section, even at the surface if the turbulence is sufficient.

Except for the Laursen equation (Shulits and Hill 1968), no listed equation predicts wash load—the movement of finer particles (usually assumed to be silt and clay) not found appreciably in the shifting portion of the streambed. Some transport equations such as Rottner, Meyer-Peter and Muller, and Kalinske (all in Shulits and Hill 1968) were not included in table 4 because these appear to be good only at predicting the bedload component.

Some of the equations, such as the Schoklitsch (Shulits and Hill 1968), are simple and predict sediment transport with as few as two variables. Others are more complex. For example, to determine a rate of sediment transport, the Einstein procedure (Einstein 1950) requires an input of about 15 flow and sediment variables and about 40 other computed variables.

One variable common to all equations is the particle size (or sizes) of the streambed sediment. Some equations were developed from uniform sediments, while others were developed with graded sediments. Both types are being used to predict transport in natural streams.

Some of the equations, such as Schoklitsch (Shulits and Hill 1968), Haywood (Shulits and Hill 1968), and Colby (1964), are empirical—they have coefficients and exponents determined graphically or statistically. Many of the others, such as Straub-

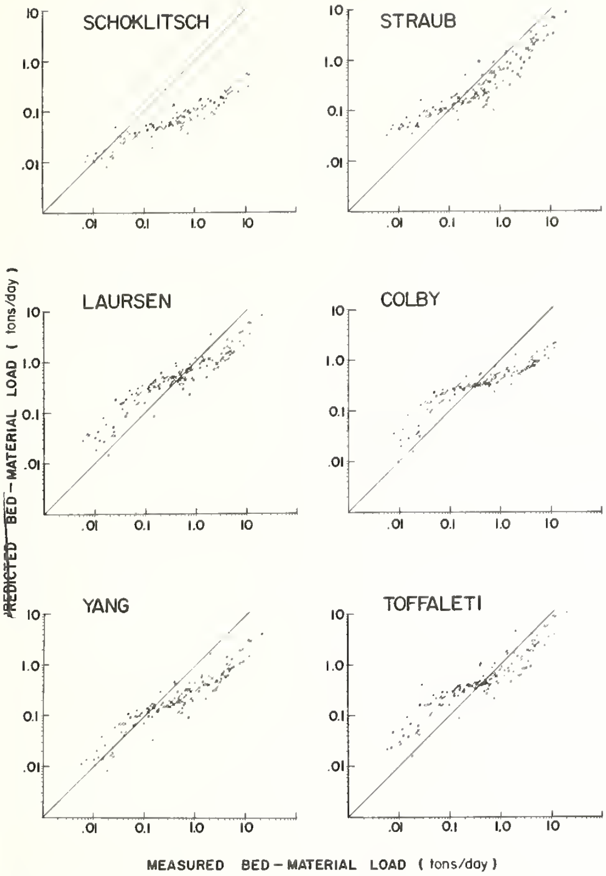

FIGURE 16.—Comparisons of predicted and observed bed-material loads on the Little Washita River near Ninnekah, Okla.

DuBoys (Shulits and Hill 1968), Einstein (1950), Bagnold (1966), and Yang (1972) are based on various theories. Even these have empirical elements, a circumstance that may explain why they generally predict no more accurately than the entirely empirical ones.

There has never been a comprehensive study to determine how accurate all these equations are in predicting bed-material transport for a range of conditions found across the United States. Several studies, however, using a few equations and a limited range of data, have shown that prediction accuracy is generally unsatisfactory.

Figures 16 and 17 show the results of one of these studies for two streams in the southern part of the Great Plains. I have assumed that the equations predict the sand fraction of the load; so predictions are compared to measured sand transports. For the Little Washita River near Ninnekah, Okla. (fig. 16), with a drainage area of 208 mi^2, predictions by the

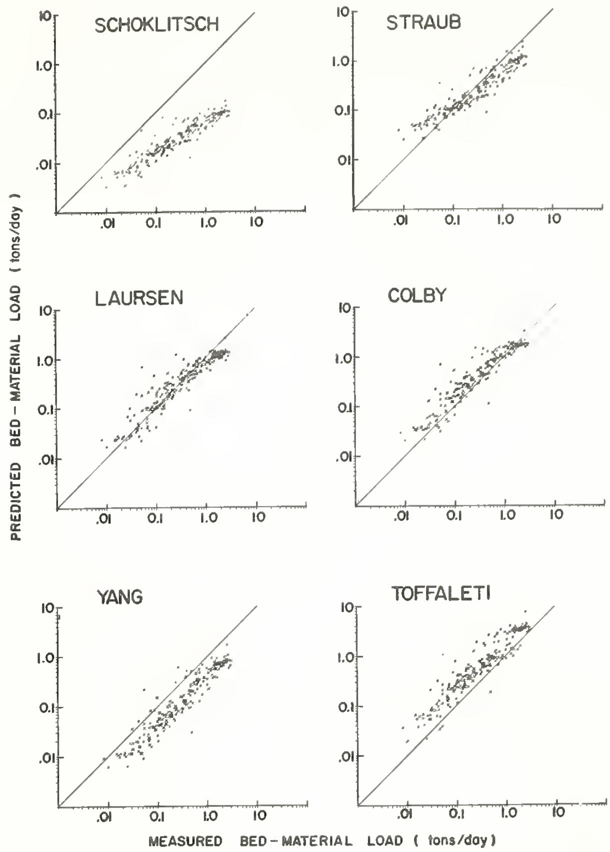

FIGURE 17.—Comparisons of predicted and observed bed-material loads on the Washita river near Alex, Okla.

six selected equations at low transport rates are about double the measured rates; predictions at high transport rates are about half the measured rates. For the Washita River at Alex, Okla. (fig. 17), with a drainage area of 4,787 mi^2, predictions with each equation were consistently high or low and ranged from roughly two times too high for the Toffaleti (1968) procedure to five times too low for the Schoklitsch equation.

SELECTION OF A METHOD

Because there are so many methods for determining sediment yield either by measurement or prediction, the following comparative discussion may help users choose the best method for a given situation. The selection depends upon such factors as watershed size, accuracy desired, resources available (labor, funds, electronic computers), time (how soon the determination is needed), detail desired (texture of the yield, instantaneous peak

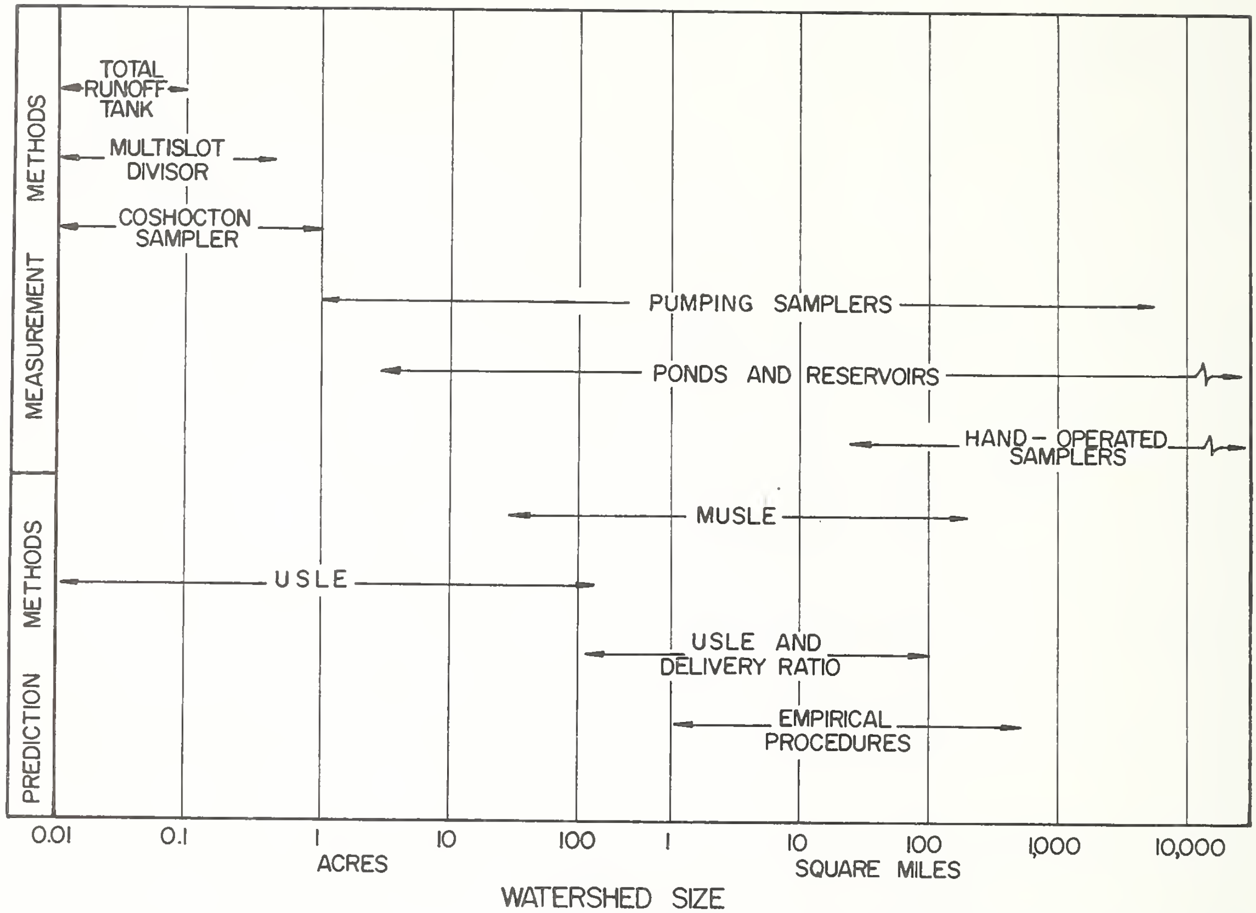

FIGURE 18.—The approximate range of watershed size applicable for each procedure for determining sediment yield.

loads, and locations of scour and deposition), and personal preference.

Figure 18 shows watershed sizes generally applicable for each method. This generality must be emphasized because other factors often restrict the applicable size range. The multislot divisor and Coshocton sampler, for example, are limited by the maximum expected runoff volume and peak. Since estimates of these are imprecise, however, the approximate applicable drainage areas are shown. The upper limit for pumping samplers (5,000 mi^2 in fig. 18) may be exceeded where channels have a low width-to-depth ratio and sediment loads are fine. But pumping samplers may have difficulty getting representative runoff samples from watersheds no larger than 200 mi^2 where conditions do not allow effective sampling—for example, a watershed having wide shallow flows with coarse sediment loads.

The minimum watershed size shown in figure 18 for hand-operated suspended-sediment samplers is about 25 mi^2. For smaller watersheds, runoff events have usually peaked before stream gagers can get to the gaging sites, so collection of storm data is incomplete. Where a stream gager lives near a gaging site, much smaller watersheds can be sampled. Also, where sediment yield is to be computed with the sediment-rating curve, sufficient sediment data for smaller watersheds can be obtained by hand.

Ranking the methods for accuracy is largely intuitive because of the lack of factual data. In figure 18, the vertical position of the method generally reflects its accuracy—the most accurate at the top, the least accurate at the bottom. Methods involving actual measurements are more accurate than the prediction methods. For most of the measurement methods, accuracies within ±15% may result most of the time. Most computations by the empirical procedures will probably err by

one or more orders of magnitude. Accuracy in determinations of sediment yield is affected by how the method is applied. For methods using suspended-sediment samples, accuracies increase, up to a point, with the frequency of sampling. For reservoir surveys, accuracies increase, up to a point, with the number of elevation observations made per unit area. Accuracy is also affected by how the data are applied. Sometimes data from one watershed are used for another. But watersheds only a few miles apart might easily have a 10-fold difference in sediment yield. Therefore, data on sediment yield in one watershed should be used for another only if the two are alike in vegetation, physiography (including soil texture), and climate.

The accuracy of sediment yields determined with methods using suspended-sediment samples will vary with the type of computation. With enough samples, the continuous-concentration-curve procedure has good accuracy. For some years, sediment yield computed by the sediment-rating-curve procedure will differ from yield determined by the continuous-concentration-curve procedure by as much as ±20%. When a sediment-rating curve developed from 1 year's data is used to compute the yield for other years, errors up to about ±50% may result. These errors are usually less for large watersheds than for small watersheds.

The prediction accuracy of the MUSLE method will vary depending on how it is applied. If it is calibrated for an area and if measured flow data are available, accuracy should approach that of the sediment-rating-curve procedure. If the MUSLE is not calibrated for an area and if flow data must be estimated, the prediction accuracy may be no better than that of the entirely empirical procedures.

For all measurement methods, obtaining long-term rates of sediment yield often depends on the term of the records. For reliable yields, measurements should span at least 3 to 5 years. The precipitation for the period should be compared to the long-term precipitation; if the two figures differ by more than about 10%, the sediment yield should be adjusted accordingly.

Costs of determining sediment yield by these methods are generally directly related to the accuracy of prediction. In figure 18, the vertical position of the method generally reflects its cost—the most expensive at the top, the cheapest at the bottom. Having data already available, however, can greatly affect the cost. For example, if usable data are on hand for computing the sediment yield in one of the measurement procedures, that procedure would change from being one of the most costly to being one of the least for any given watershed.

The newer physically based, distributed-parameter models have not been included in figure 18 because they are complex, they have not been tested, and they have not been developed for large watersheds. One or more of these could be used for estimating relative sediment yield under various land uses or treatments and for finding out where erosion and deposition have occurred.

Photogrammetric determination of erosion was also excluded from figure 18. This measurement method, based on determining changes in land elevation, is limited to those areas with high erosion rates. The great investment in equipment and worker training is a further economic restraint that limits the method to large or very long-term projects.

REFERENCES

Allen, Paul B.; Welch, Norman H.; Rhoades, Edd D.; Edens, Carlton D.; and Miller, Gary E.

1976. The modified Chickasha sediment sampler. U.S. Agric. Res. Serv. [Rep.] ARS-S-107, 13 pp. (Available from the Science and Education Administration, P.O. Box 400, Chickasha, Okla. 73018.)

Anderson, Henry W.

1949. Flood frequencies and sedimentation from forested watersheds. Trans. Am. Geophys. Union 30: 567-584.

Bagnold, R.A.

1966. An approach to the sediment transport problem from general physics. U.S. Geol. Surv. Prof. Pap. 422-I, 37 pp.

Baird, Ralph W.

1964. Sediment yields from Blackland watersheds. Trans. ASAE 7: 454-456.

Beasley, D.B.; Monke, E.J.; and Huggins, L.F.

1977. The ANSWERS model: A planning tool for watershed research. Am. Soc. Agric. Eng. Pap. 77-2532, 21 pp.

Betson, Roger.

1976. Urban hydrology. A systems study in Knoxville, Tennessee. 137 pp. Tennessee Valley Authority, Knoxville, Tenn.

Colby, B. R.

1956. Relationship of sediment discharge to streamflow. Open-File Report, U.S. Geological Survey, Washington, D.C., 170 pp.

1957. Relationship of unmeasured sediment discharge to mean velocity. Trans. Am. Geophys. Union 38: 708-717.

1964. Discharge of sands and mean-velocity relationships in sand-bed streams. Sediment transport in alluvial channels. U.S. Geol. Surv. Prof. Pap. 462-A, 47 pp.

Colby, B. R., and Hubbell, D. W.

1961. Simplified methods for computing total sediment discharge with the modified Einstein procedure. U.S. Geol. Surv. Water-Supply Pap. 1593, 17 pp.

Corbett, Don M., and others.
1943. Stream-gaging procedure. A manual describing methods and practices of the geological survey. U.S. Geol. Surv. Water-Supply Pap. 888, 245 pp.

Dendy, F. E., and Bolton, G. C.
1976. Sediment yield-runoff-drainage area relationships in the United States. J. Soil Water Conserv. 31: 264-266.

Dendy, F. E., and Champion, W. A.
1978. Sediment deposition in U.S. reservoirs. Summary of data reported through 1975. U.S. Dep. Agric. Misc. Pub. 1362, 82 pp. (Available from Publications Requests and Distribution, SEA Information Staff, Room 6007, U.S. Department of Agriculture, Washington, D.C. 20250.

Druffel, L.; Emmett, W. W.; Schneider, V.; and Skinner, J.
1976. Laboratory hydraulic calibration of the Helley-Smith bedload sediment sampler. U.S. Geol. Surv. Open-File Rep. 76-752, 63 pp.

Einstein, Hans Albert.
1950. The bed-load function for sediment transportation in open channel flows. U.S. Dep. Agric. Tech. Bull. 1026, 71 pp. (Out of print.)

Federal Inter-Agency Sedimentation Project.
1974. A study of methods used in measurement and analysis of sediment loads in streams. Catalog. Instruments and reports for fluvial sediment investigations. 56 pp. Federal Inter-Agency Sedimentation Project, St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minn.

Flaxman, Elliott M.
1972. Predicting sediment yield in western United States. Proc. Am. Soc. Civ. Eng. Hydrol. Div. HY12: 2073-2085.

Foster, G. R.; Meyer, L. D.; and Onstad, C. A.
1977. A runoff erosivity factor and variable slope length exponents for soil loss estimates. Trans. ASAE 20: 683-687.

Frere, M. H.; Onstad, C. A.; and Holton, H. N.
1975. ACTMO. An agricultural chemical transport model. U.S. Agric. Res. Serv. [Rep.] ARS-H-3, 54 pp. (Available from Publications Requests and Distribution, SEA Information Staff, Room 6007, U.S. Department of Agriculture, Washington, D.C. 20250.)

Hindall, S. M.
1976. Prediction of sediment yields in Wisconsin streams. Proc. Fed. Inter-Agency Sediment. Conf., 3d, 1976, 1-205—1-218.

Lane, E. W., and Borland, W. M.
1951. Estimating bed load. Trans. Am. Geophys. Union 32: 121-123.

Maner, Sam B., and Barnes, Leland H.
1953. Suggested criteria for estimating gross sheet erosion and sediment delivery rates for the Blackland Prairies problem area in soil conservation. 32 pp. U.S. Soil Conservation Service, Western Gulf Region, Fort Worth, Tex.

Miller, C. R.
1951. Analysis of flow-duration, sediment-rating curve method of computing sediment yield. 55 pp. U.S. Bureau of Reclamation, Denver, Colo.

Piest, R. F.; Spomer, R. G.; and Muhs, P. R.
1977. Profile of soil movement on a cornfield. *In* Soil Erosion, Prediction and Control, pp. 160-166. Soil Conserv. Soc. Am. Spec. Pub. 21.

Rhoades, Edd D.; Welch, Norman H.; and Coleman, Gerald A.
1975. Sediment-yield characteristics from unit source watersheds. *In* Present and Prospective Technology for Predicting Sediment Yields and Sources, pp. 125-129. U.S. Agric. Res. Serv. [Rep.] ARS-S-40. (Out of print.)

Shulits, Sam, and Hill, Ralph D., Jr.
1968. Bedload formulas. Pennsylvania State University, Department of Civil Engineering, Hydraulics Laboratory Bulletin, University Park, Penn., 212 pp.

Simons, D. B.; Li, R. M.; and Stevens, M. A.
1975. Development of models for predicting water and sediment routing and yield from storms on small watersheds. Colo. State Univ. Civ. Eng. Dep. Rep. CER-74, 130 pp.

Spraberry, James A.; Woodburn, Russell; and McHenry, J. Roger.
1960. Sediment delivery ratio studies in Mississippi. I. A preliminary report. Agron. J. 52: 434-436.

Stewart, B. A.; Woolhiser, D. A.; Wischmeier, W. H.; Caro, J. H.; and Frere, M. H.
1975. Control of water pollution from cropland. Vol 1. A manual for guideline development. U.S. Agric. Res. Serv. Rep. ARS-H-5-1; Environ. Prot. Agency U.S. Rep. EPA-600/2-75-026a, 111 pp. (Available from Publications Requests and Distribution, SEA Information Staff, Room 6007, U.S. Department of Agriculture, Washington, D.C. 20250.)

Striffler, W. David.
1964. Sediment, streamflow, and land use relationships in northern Michigan. U.S. For. Serv. Res. Pap. LS-16, 12 pp.

Toffaleti, F. B.
1968. A procedure for computation of the total river sand discharge and detailed distribution, bed to surface. U.S. Army Corps Eng. Comm. on Channel Stabilization Tech. Rep. 5, 172 pp.

U.S. Inter-Agency Committee on Water Resources. Subcommittee on Sedimentation.
1963. A study of methods used in the measurement and analysis of sediment loads in streams. Report No. 14. Determination of fluvial sediment discharge. 151 pp. St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minn.

U.S. Science and Education Administration.
1979. Field manual for research in agricultural hydrology. U.S. Dep. Agric. Agric. Handb. 224, 547 pp. (For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, Stock Number 001-000-03798-6.)

U.S. Soil Conservation Service.
1976. Guide to sedimentation investigations. U.S. Soil Conserv. Serv. South Reg. Tech. Serv. Cent. Tech. Guide 12, 75 pp.

Williams, Jimmy R.
1975. Sediment-yield prediction with universal equation using runoff energy factor. *In* Present and Prospective Technology for Predicting Sediment Yields and Sources, pp. 244-252. U.S. Agric. Res. Serv. [Rep.] ARS-S-40. (Out of print.)

Williams, J. R.; Hiler, E.A; and Baird, R. W.
1971. Prediction of sediment yields from small watersheds. Trans. ASAE 14: 1157-1162.

Wischmeier, W. H.
1976a. Cropland erosion and sedimentation. *In* Control of Water Pollution From Cropland. Vol. 2. An Overview. U.S. Agric. Res. Serv. Rep. ARS-H-5-2; Environ. Prot. Agency U.S. Rep. EPA-600/2-75-026b, pp. 31-57. (Available from Publications Requests and Distribution, SEA Information Staff, Room 6007, U.S. Department of Agriculture, Washington, D.C. 20250.)
1976b. Use and misuse of the universal soil loss equation. J. Soil Water Conserv. 31: 5-9.

Wischmeier, Walter H., and Smith, Dwight D.
1978. Predicting rainfall erosion losses. A guide to conservation planning. U.S. Dep. Agric. Handb. 537, 58 pp. (Available from Publications Requests and Distribution, SEA Information Staff, Room 6007, U.S. Department of Agriculture, Washington, D.C. 20250.)

Yang, Chih Ted.
1972. Unit stream power and sediment transport. Proc. Am. Soc. Civ. Eng. Hydrol. Div. HY10: 1805-1826.

U. S. DEPARTMENT OF AGRICULTURE
SCIENCE AND EDUCATION ADMINISTRATION
P. O. BOX 53326
NEW ORLEANS, LOUISIANA 70153

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

POSTAGE AND FEES PAID
U. S. DEPARTMENT OF
AGRICULTURE
AGR 101

U.S.MAIL

FIRST CLASS

☆ U.S. GOVERNMENT PRINTING OFFICE: 1981— 771-039/41B